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# A review of researches on thermal exhaust heat recovery with Rankine cycle

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ABSTRACT

Internal combustion (IC) engines are the major source of motive power in the world, a fact that is expected to continue well into this century. To increase the total efficiency and reduce $CO_2$ emissions, recently exhaust heat recovery (EHR) based on thermoelectric (TE) and thermal fluid systems have been explored widely and a number of new technologies have been developed in the past decade. In this paper, relevant researches are reviewed for providing an insight into possible system designs, thermodynamic principles to achieve high efficiency, and selection of working fluids to maintain necessary system performance. From a number of researches, it has been found the Rankine cycle (RC) has been the most favourite basic working cycle for thermodynamic EHR systems. Based on the cycle, various different system configurations have been investigated. Accepting a certain design and manufacture cost, a system based on heavy duty vehicle application can increase the total powertrain efficiency by up to 30% (based on NEDC driving condition). To achieve the highest possible system efficiency, design of systemic structure and selections for both the expander and the working fluid (medium) are critical.



**Contents**



## 1. Introduction

In recognition of the need to further reduce vehicle exhaust emissions and the greenhouse gas $CO_2$, there has been a lot of interest in the development of cleaner and more efficient energy saving vehicle powertrain. With the cost of obtaining even a 1% increase on the engine combustion efficiency is significant, recently technology development has concentrated on possible hybrid configuration (HEV) and new EHR. Here, new EHR means those new technologies beyond conventional uses for exhaust waste heat such as turbocharger or cabin air-heating. While HEV technology has achieved considerable market share in recent years, R&D on EHR needs to be paid more attention, particularly as while energy collected by EHR can be easily applied on HEVs.

Since it is difficult for the maximum efficiency of IC engines to be higher than 42% [1], large amount fuel energy is rejected from the engine to the surroundings as waste heat in several forms, with a significant fraction through the exhaust. A recent study [2] estimated in a typical 2 l gasoline engine used on passenger cars, 21% of the released energy is wasted through the exhaust at the most

*Abbreviations:* IC, Internal combustion; EHR, Exhaust heat recovery; TE, Thermoelectric; RC, Rankine cycle; HEV, Hybrid electric vehicle; LDP, Light-duty passenger; HD, Heavy-duty; DPF, Diesel particulate filter; ALPING, Advanced injection low pilot ignition natural gas; T, Turbine; LPSRC, Low pressure steam Rankine cycle; HPSRC, High pressure steam Rankine cycle; RS, Recovery sub-system; HICE, Hydrogen internal combustion engine; EGR, Exhaust gas recirculation; FMG, Flywheel motor/generator; C, Compressor; ACAC, Air-cooled charge air cooler; HPP, High pressure pump; LPP, Low pressure pump; WFR, Working fluid reservoir; HT, High temperature; LT, Low temperature; CAC, Charge air cooler; BSFC, Brake specific fuel consumption (g/s/W); Cp, Critical point.

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**Nomenclature**

| | |
|---|---|
| *T* | *Temperature (°C)* |
| *s* | Specific entropy (kJ/(kg K)) |
| $\dot{Q}$ | Heat transfer rate (kW) |

*Greek symbols*

| | |
|---|---|
| $\eta$ | Thermal efficiency |
| $\lambda$ | Excess air ratio |

*Subscripts*

| | |
|---|---|
| L | Condensation |
| C | Critical temperature |
| H | Evaporation temperature |
| CC | Engine with combined cycle |
| e | Prototype engine with no EHR |

common load and speed condition. This increases to 44% at the peak power point. On average, about one third of energy generated from the fuel is wasted via exhaust gases. Current estimates of waste thermal energy from light-duty vehicle systems range from 20 kW to 400 kW, depending on engine size and engine torque-speed conditions. This is equivalent of annually 45 billion gallons of gasoline fuel lost through the exhaust pipes of the 240 million light-duty passenger (LDP) vehicles in USA alone [3].

LDP vehicle exhaust system operates at gas temperatures from 500 to 900 °C, typically between 600 and 700 °C, while it ranges from 500 to 650 °C for heavy-duty (HD) vehicle [3]. These can be further boosted during periodical regenerations of diesel particulate filter (DPF) and other aftertreatment devices [4]. Those high exhaust temperatures provide significant opportunities for EHR to generate energy for various applications.

The converting of exhaust heat into useful power would not just bring measurable advantages for improving fuel consumption but also increase engine power output (power density) or downsizing, further reducing $CO_2$ and other harmful exhaust emissions correspondingly. It was predicted by Vazaquez et al. [5] that if only 6% of the heat contained in the exhaust gases were converted to electric power, this would mean reduction of fuel consumption by 10% due to the decrease in mechanical losses from the resistance of the alternator drive. In addition, the experimental work conducted by Honda (Endo et al. [6]) with a thermal recovery system showed a maximum thermal cycle efficiency of 13%. At 100 km/h, this yields a cycle output of 2.5 kW (for an engine output of 19.2 kW), representing an increase in the thermal efficiency of the engine from 28.9% to 32.7%.

As well as conventional technologies such as turbocharger, cabin air-heating [7–14], desalination [15–18] and reducing engine warm-up time [19–21] which use exhaust waste heat, currently major new technologies for EHR include turbo-compounding and thermal EHR based on RC and TE regeneration. The latter can directly convert part of the exhaust heat to electric power through the thermoelectric phenomenon, without the use of mechanically rotating parts, and providing some advantages such as completely solid state, no noise, no vibration, sometime no moving fluids and high reliability. However, there exist significant system design challenges during the development of the TE due to its low conversion efficiency with current technology and the relatively high costs of the thermoelectric semiconductor materials [22–27].

Turbo-compounding systems have also been developed rapidly in recent years. However, the fatal disadvantages in the increasing of the engine backpressure and pumping losses [28] have hauled the taking off of those systems as expected. Between RC system and turbo-compounding for EHR, Weerasinghe et al. [29] made a numerical simulation comparing their power output and fuel saving. The results reveal the relative advantages of RC over turbo-compounding are: (1) at least two percentage points of more power can be developed; (2) fuel savings of 20% or more compared to around 2.0% savings. The outstanding heat storage ability of the steam reservoir that acts as an energy buffer was highlighted to make RC favored against turbo-compounding systems. Another advantage provided by RC system over turbo-compounding system is the improvement of the turbocharger's low-speed response if a turbocharger is fitted upstream.

In this paper, relevant researches will be studied with an emphasis on thermal EHR systems of RC which are normally located after turbocharger (if equipped). Work and results on system designs, subsystem parameters, working fluid influences, vehicle operating condition considerations etc. will be reviewed for providing an insight into system performance and its effect on the total energy efficiency of powertrain systems.

## 2. Energy characteristics in exhaust gases

For the purpose of exhaust heat regeneration, Chammas and Clodic [2] analysed relevant characteristics of exhaust gases from a typical light duty 4 cylinder spark ignition engine, such as the exhaust temperature and the available exhaust gas energy, and found the exhaust waste heat ranges from 4.6 to 120 kW depending on conditions while the cooling water heat ranges from 9 to 48 kW. The peak temperatures of exhaust gases reached was close to 900 °C with the coolant temperature around 100 °C. And their results suggest the maximum work for energy generation is from 1.7 to 45 kW when the regeneration system operates between the average temperature of the exhaust gases and the outdoor temperature.

Teng et al. [4] assessed the variation of exhaust gas temperature with the engine speed of a typical truck diesel engine under full load condition (as shown in Fig. 1) and evaluated the exergy value from the exhaust gas, as shown in Fig. 2. Here, exergy means the available energy from exhaust gas for useful work. The definition has been used in some researches as a more appropriate parameter for estimating energy levels of different sources of waste heat. As shown in Fig. 2 [4], the exergy of exhaust is more than 30% of its energy value at exhaust temperatures around and greater than 600 °C, but decreases with the reduction of exhaust temperature.

In researches of Hung et al. [30] and Larjola [31], it has been demonstrated that up to 50% of exergy of exhaust gas can be recovered when a RC–EHR system is employed. This means an EHR system based on RC can help the engine get an increase in power

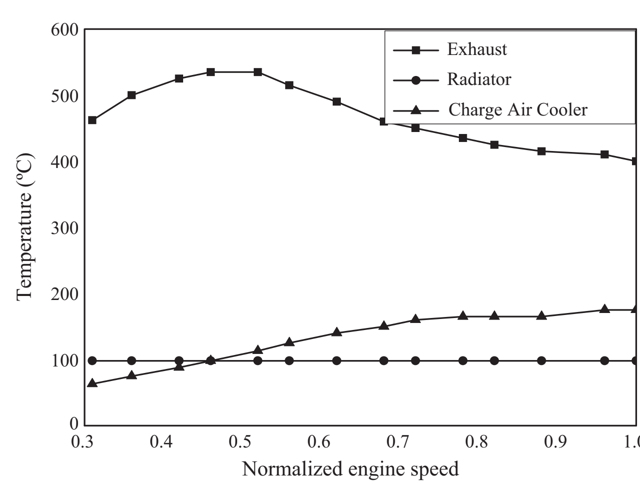


**Fig. 1.** Exhaust temperatures of a typical truck diesel engine at full load.

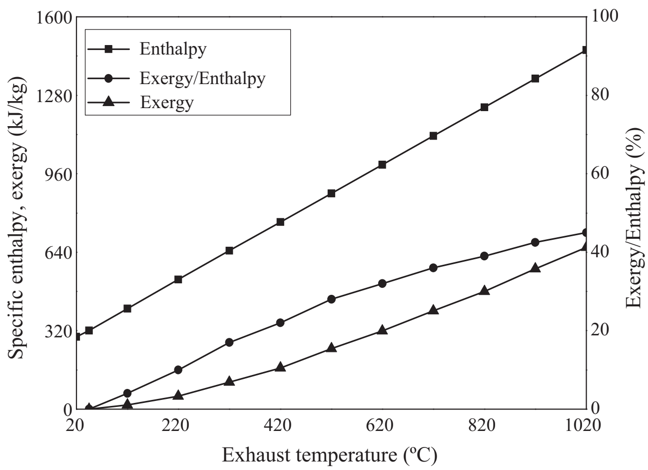


**Fig. 2.** Exergy of exhaust of a typical truck diesel engine at full load ($T_{ambient}$ = 20 °C, $\lambda$ = 1.5).

output by over 10%, or an improvement in the overall engine efficiency by greater than 10% [4]. Other similar researches, such as the work developed by Cummins, Inc. [32,33] also using a RC system, suggested it is possible for Class 7–8 highway trucks to increase its overall engine efficiency to be more than 50%. Results from several researches which based on the exergy analysis in terms of the second law all reveal the exhaust waste heat is of particular interest for EHR. As demonstrated from the analysis, the potential for recovering exhaust heat and converting it into useful mechanical or electrical energy is significant.

It is evident the optimal steam conditions for RC are those which produce the greatest power output. However, it has been demonstrated this depends on the steam generator pinch temperature difference, primary engine load and the rated power. Hence the optimal conditions change with load [34]. The investigation conducted by Marner [35] has shown that engine load will affect the amount of available heat for the EHR system.

Ringler et al. [36] plotted a graph, as shown in Fig. 3, for presenting the heat flows for various vehicle speeds (45, 55, 70 and 80 mph), based on their investigation on a medium duty vehicle. For velocities between 45 and 80 mph, the exhaust gas heat flow ranges between ~5 and ~30 kW, while the coolant heat flow changes from ~9 to ~20 kW. This could be explained by the fact that the need of

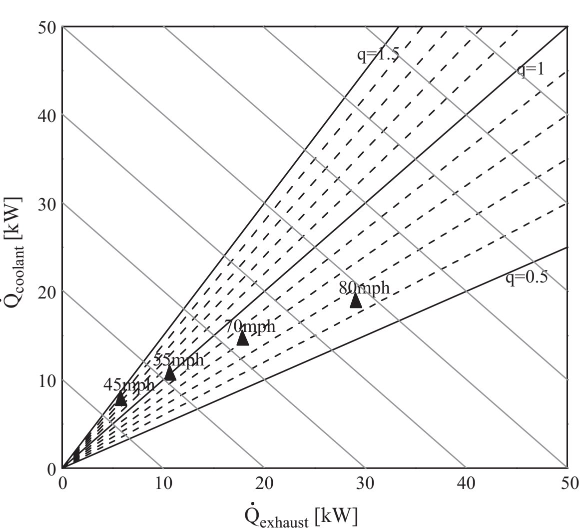


**Fig. 3.** Heat flow $\dot{Q}_{coolant}$ and $\dot{Q}_{exhaust}$ at different vehicle cruising speeds.

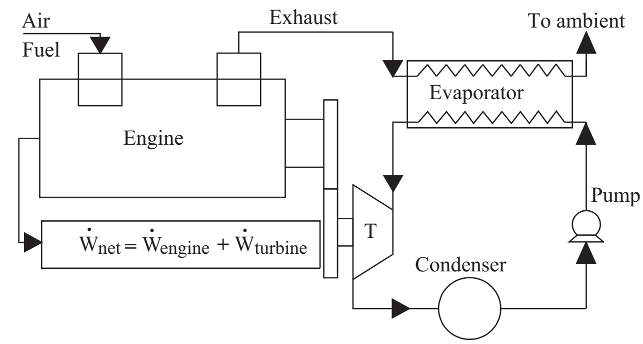


**Fig. 4.** Schematic of setup used for RC EHR.

more power for the increased driving speed will increase higher waste heat flows. The two waste heats have a ratio close to 1:1 at ~55 mph, with the coolant at lower speeds and the exhaust gas at higher speeds dominating as a heat source.

Chammas and Clodic [2] reached a similar conclusion from their study on 1.4 l spark ignition engine. While heat in the exhaust was half of that in the coolant at 1500 rpm and 1/4 load (21% vs. 42%), the ratio of the two heat flows reversed direction at 4500 rpm with 44% vs. 18%. These results suggest the engine operational conditions should be taken into consideration when a RC–EHR system is designed and optimized for vehicle application. Of course, an ideal case is that the engine load and speed are stable over a large portion of operation hours. This is why Teng et al. [37] prefer to apply EHR on HD diesel trucks.

## 3. Thermal recovery systems based on Rankine cycle

Applications of RC for EHR on on-road vehicles were first investigated during the energy crisis in 1970s [38–40], but mainly for HD trucks. For instance, Patel and Doyle from Mack Trucks [41] designed and built a prototype of such a system operating on the exhaust gas of a 288 HD truck engine in 1976. A 450 km on-road test demonstrated the technical feasibility of the system and its economical advantage with an improvement of 12.5% in fuel consumption. Following this, based on the work by Thermo Electron Corporation, Heywood [42] claimed a prediction in 1981 that a reduction of fuel consumption by 10–15% could be obtained with a RC–EHR system on diesel engines.

Recent examples using the basic RC for EHR can be found from the research conducted by Srinivasan et al. [43] (2008), who coupled a simple RC operating on an Advanced Injection Low Pilot Ignition Natural Gas (ALPING) engine. As shown in Fig. 4, the energy output was through a turbo compounded to the crankshaft of the engine to improve the total power output and the fuel economy as well as reduce brake-specific emissions. It was demonstrated the RC system contributed a fuel conversion efficiency improvement of the order of 10% at half load operation while maintaining the essential low NO*x* characteristics of ALPING combustion.

Other recent researches include the work of Chammas and Clodic [2] (2005), who tried to combine the working cycle for HEV application. In their system, the energy output was implemented by an electric generator then flows to the electric system of HEV. The evaporator was installed on the exhaust line downstream of the catalytic converter to avert the effect on the aftertreatment performance. The turbine/generator system converted the recovered exhaust waste heat into electrical power, of avail for assisting the engine, battery charging or covering the onboard electrical power demand. The fuel economy improvements measured was up to 24.7% at low load condition, and increased with the increase of the engine load and speed. They claimed up to 32% improvement of

**Table 1**
Comparison of fuel energy distribution between with and without EHR at 1500 rpm and 1/4 load.

| | Without EHR[a] | With LPSRC[b] | With HPSRC[c] | With ORC[d] |
|---|---|---|---|---|
| Engine output | 19% | 18.80% | 18.80% | 18.80% |
| Exhaust waste | 21% | 6.40% | 6.40% | 8.60% |
| Engine cooling | 42% | 41.80% | 41.80% | 0 |
| Other losses | 18% | 18% | 18% | 18% |
| Electrical output | | 1.30% | 2% | 4.90% |
| Condense waste | | 13.40% | 12.60% | 48.80% |
| Generator losses | | 0.30% | 0.40% | 0.90% |
| Fuel economy improvement | | 5.8% | 9.5% | 24.7% |

[a] 1.4 l spark ignition engine.
[b] Low pressure steam Rankine cycle.
[c] High pressure steam Rankine cycle.
[d] Organic Rankine cycle (isopentane or R-245 ca).

fuel economy could be achieved under the full load. Table 1 shows fuel energy distribution data of their investigation with different system configurations.

Most systems developed today are very different from those using basic RC employed in 1970s because of the advances in the development of expansion devices and the broader choice of working fluids. There has been a massive resurgence of interest in adopting RCs, particularly using organic fluids, to enable EHR. BMW (2005, [44]) employed a dual RC system for passenger car applications, with a high temperature steam RC in parallel with a low temperature RC, where expanders were used to produce mechanical work.

Yamada and Mohamad [45] proposed a novel waste heat recovery sub-system on a hydrogen internal combustion engine (HICE), where two potentially valuable products of combustion with large amount were exploited at the same time, water to be the working fluid for an open-cycle power generation system based on the Rankine cycle, while exhaust waste heat to be used to superheat the fluid. Another interesting consideration in their system is that two options were proposed for sub-system I (RS-I) without a condenser and the sub-system II (RS-II) with a condenser and electric fan, as shown in Fig. 5. RS-I was claimed to be a better choice than RS-II in terms of cost effectiveness and smaller system design, though RS-II showed a slightly higher thermal efficiency. Their experimental results combined with RS-I showed an overall thermal efficiency increase by 2.9% to 3.7% in the engine speed range of 1500–4500 rpm.

In Vaja and Gambarotta's work [46], one cycle but two heat exchangers were included with the first exchanger before the main evaporator for preheating the working fluid, but with a different system design. As shown in Fig. 6, the first design has a pre-heater for which the thermal energy is supplied by the engine coolant cycle, while the main heater was supported by the exhaust gas energy. In their second design shown in Fig. 7, the pre-heater/recuperator is heated by the used steam from the expander of RC. The improvements of efficiency are shown in Table 2. In their conclusion, it showed they preferred to employ the former scheme due to its relative simpler components.

However, Arias et al. [47] were not so optimistic on preheating with engine coolant. They analysed a similar system preheated by

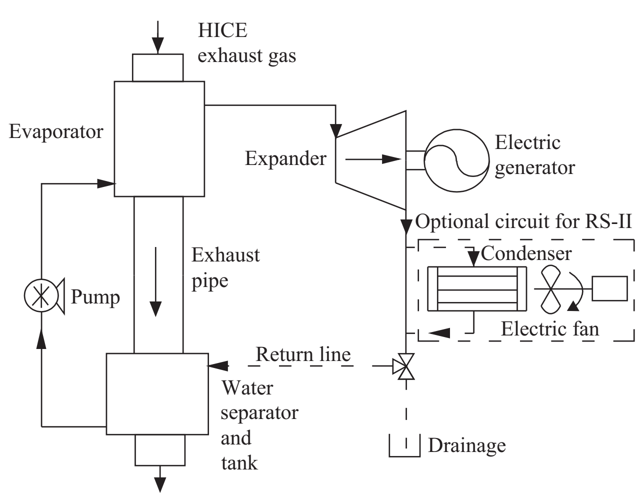


**Fig. 5.** RC system with two heat exchangers and for with and without condenser.

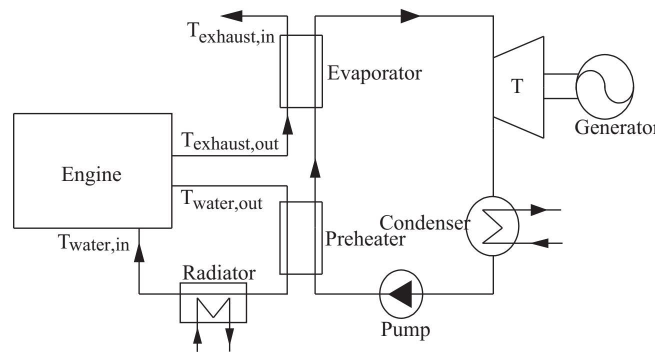


**Fig. 6.** RC system with a pre-heater heated by the engine coolant cycle.

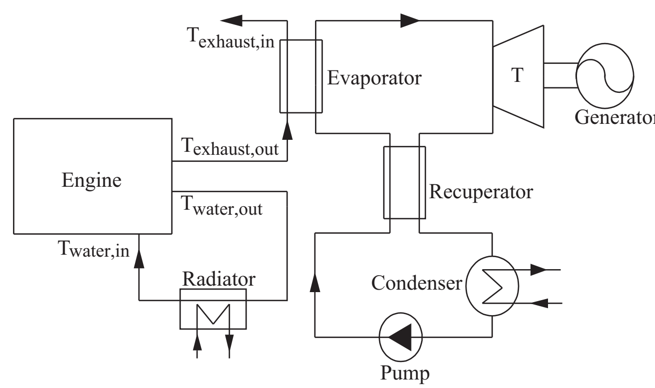


**Fig. 7.** RC system with a recuperator heated by the used steam.

**Table 2**
Combined IC engine organic RC efficiencies.

| | Simple RC | RC with preheater | RC with recuperator |
|---|---|---|---|
| $\eta_{CC}$ | 0.466 | 0.471 | 0.471 |
| $\eta_{CC}/\eta e$ | 0.114 | 0.126 | 0.128 |

$\eta_{CC}$: thermal efficiency of engine with combined cycle; $\eta_e$: thermal efficiency of the prototype engine with no EHR.

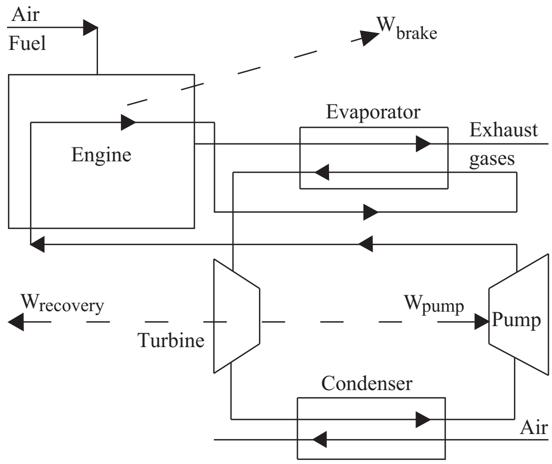


**Fig. 8.** RC with energy recovery from engine block and exhaust gases.

the engine coolant and found a very similar performance between with and without the engine coolant preheating to the RC working fluid. This is due to the constraint imposed on the temperature of the engine coolant, which was so low that it was not a good match for the preheating of working fluid. Correspondingly, they proposed a new fluid cycle, as shown in Fig. 8, with preheating carried out by the engine block. A better match between the temperatures of the energy sources was achieved with the engine block used to pre-heat the fluid and the high temperature exhaust gases for superheating the fluid.

With a complicated system, Teng and Regner [48] exploited waste heat from the EGR system of a class-8 truck diesel engine to operate a supercritical RC with R245fa as working fluid, as demonstrated in Fig. 9. The fluid was superheated upstream of the expander, which was coaxially assembled with the alternator. The system achieved a 15.8% Rankine efficiency, which could reach to 25.5% with ethanol as a substitute fluid. The composite fuel savings over the ESC 13-mode test cycle was up to 5%.

Teng et al. [4] shared the same view on using waste heat of EGR system, but joined it with the main exhaust heat recovery. The charge air cooler and EGR cooler were integrated in the RC loop as pre-heaters and the RC working fluid served as the coolant for these coolers, presented in Fig. 10. This arrangement skillfully realized a supercritical RC–EHR without using a high-cost evaporator and achieved a better system performance.

Miller et al. [49] put forward a concept of dual-cycle using thermoelectric conversion integrated with a RC, a system with unique and technologically useful characteristics. In their system, the thermoelectric generator was operated by utilizing higher-temperature waste heat, while the organic RC cycle would operate to recover a large portion of the remaining low temperature thermal energy. As expected, a higher total efficiency, about 15% for power generation efficiency, was achieved with the dual-cycle system, while the high cost will be a significant factor in its application in the near future.

In summary, performance of these prototypes developed with various system configurations based on RCs is promising, and there are indications that the use of a RC can result in a significant reduction of BSFC, in the range of 10% on the entire engine operating range (load) with current technology. Of course, this solution still requires detailed investigation because various issues exist, i.e. complexity, size, weight, cost, durability etc. Further work could include developing smaller systems with acceptable performance, innovative working fluids with low environmental impact, and advanced mechanical and thermal components for low cost and high performance [49].

## 4. Effects of expander on Rankine cycle

The expander significantly determines the way in which work is delivered and the complexity of supporting hardware. Its choice strongly depends on the available inlet and outlet conditions, space and weight restrictions, working medium and the size of the system [34,50]. Depending on different system requirements, there are two options for the expander used in RC system – one is steam turbine while the other is reciprocating expander usually with a piston.

In the case of turbine-propelled cycle, as depicted by Stobart and Weerasinghe [34], steam expands adiabatically across a series of rotating blades, the turbine operates between the evaporator pressure and the condenser pressure. They favored its major attraction of the relative higher overall efficiency in operation, however, they also pointed out its poor performances in response to velocity changes and starting torque characteristics. Thus, they suggested that turbine-type expanders are preferred to be applied when the

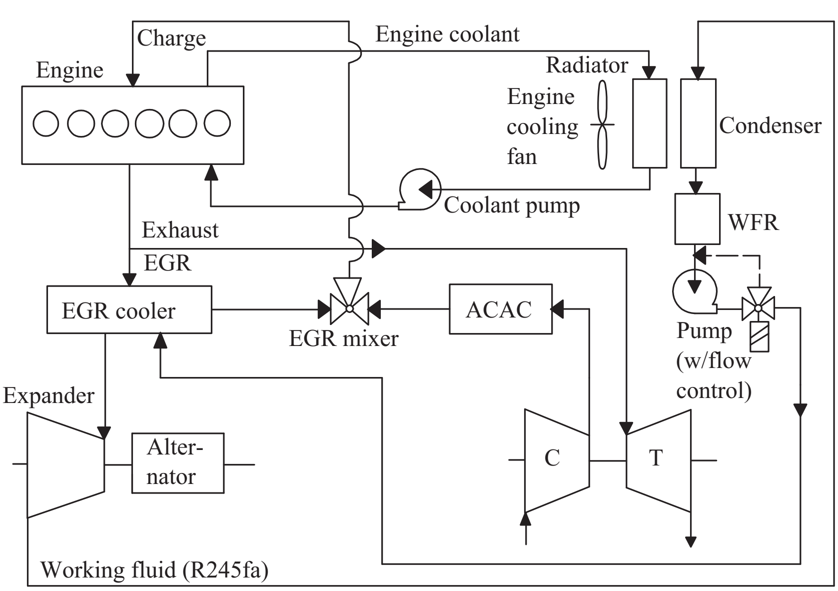


**Fig. 9.** A RC system for just recovering waste heat from EGR.FMG: flywheel motor/generator; WFR: working fluid reservoir; ACAC: air-cooled charge air cooler; EGR: exhaust gas recirculation;T: turbine; C: compressor.

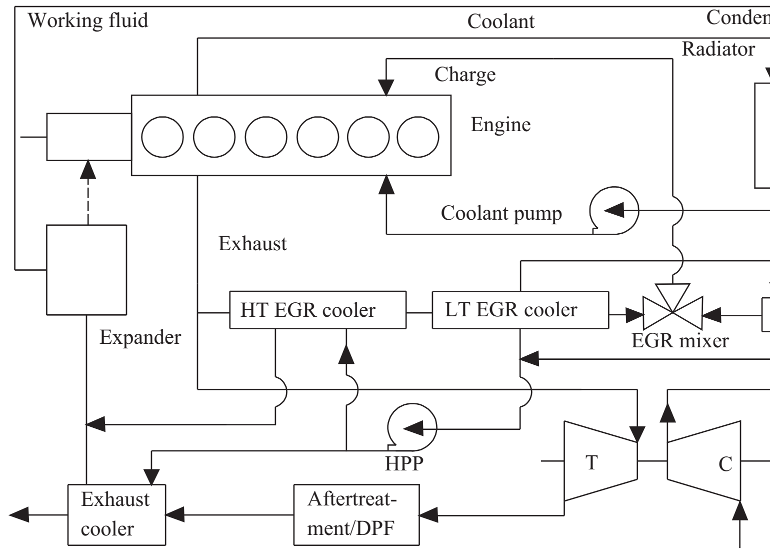


**Fig. 10.** A RC EHR system with integrated low-temperature cooling loop; LPP: low pressure pump; HPP: high pressure pump; CAC: charge air cooler; HT: high temperature; LT: low temperature; T: turbine; C: compressor.

energy developed is converted into electrical energy, with the potential to be a practical solution for hybrid vehicles. In contrast, the reciprocating-type expander seems to be considered more appropriate for combining mechanical energy output directly to the crank shaft, in particular for on-road vehicle applications where the condition for waste heat is variable, by reason of its flexibility of operation. This could offer excellent starting characteristics that eliminate the need for gearing in most of the operating range, offsetting the efficiency factor [4,37].

Investigation conducted by Quoilin and Lemort [50] revealed most of RC systems used in automotive applications employ positive displacement machines, with one exception of the RC system proposed by Cummins (Nelson [51]), which is associated to a truck engine and uses a turbo-machine. BMW (Freymann et al. [52]) initially used two vane expanders (one for each cycle), only to replace them by axial piston machines which showed efficiencies of 55% and they mentioned this could probably be improved, given that the prototype is non-optimized. Honda (Endo et al. [6]) designed a compact swash plate axial piston type expander, comprising of an oil gear pump and a generator motor mounted coaxially with the expander.

Because the turbine speed is much higher relative to HD diesel engines, a speed reduction gearbox must be employed when turbine-type expander is used. Consequently, Teng et al. [4,37] suggested that the effective work brought by the turbine-type expander is much less than the theoretical value owing to the loss in power compounding. Besides, researchers are concerned about the higher cost of turbine compared to reciprocating-type expander, due to the fact that the turbine blades and housing must continuously withstand high mechanical/thermal stresses. On the contrary, the speed of the reciprocating piston engine can be close to speeds of HD diesel engine. Hence, a simple belt compounding is possible. After a comprehensive consideration, they believe that the effective power output of the turbine would be similar to that of the reciprocating piston expander.

Previous study carried out by Teng et al. [4,37] indicated that steam turbine is restricted to steady-flow applications. Otherwise, if the heat addition is variable, the wetness in the late expansion stage may not be controllable. In cases where under-heating is encountered, the wetness of the vapor flowing through the turbine may become too high, generating an undesired working condition for the turbine. The specific volume of the working fluid at the turbine exit is limited by the turbine flow area. If the specific volume ratio across the turbine exceeds certain limit, a multi-stage turbine may have to be used.

However, from the standpoint of technical level, the reciprocating expander has not been developed as maturely as turbine-type expander, in particular for large RC units. For most applications of positive displacement expanders, the machine is often obtained by modifying existing compressors, such as used by Zanelli and Favrat [53], Yanagisawa et al. [54], Aoun and Clodic [55] and Lemort et al. [56]. The complexity of extra lubrication system gives rise to an additional difficulty in the use of a reciprocating expander, since an oil separator would be installed at the expander exhaust and an oil pump would be needed to drive the separated oil back to the expander suction [50]. In the interest of having a simple lubrication system, Teng and Regner [48] preferred using a rotary type machine as the expander employed for their EHR system on class-8 trucks.

With regard to the working pressure, Chammas and Clodic's [2] survey discovered that most of the existing expander technologies could only withstand up to 35 bar, while a swash-plate piston expander developed by Endo et al. [6] could operate up to 100 bars.

To conclude, expander technology is a key issue in RC systems. Reciprocating expanders are preferably used for locomotives, ships and stationary engines, while steam turbines are used principally in power generation and show a higher degree of technical maturity [34,50].

## 5. Working fluid

In a RC, the working fluid or medium, characterized by repeatedly vaporized, expanded and re-condensed, is considered by Ringler et al. [36] as a crucial factor in determining the potential as well as the cost effectiveness of a heat recovery system. Teng et al. [1] suggested that the efficiency of the RC varies considerably with the thermodynamic properties of its working fluid. Their research results demonstrated that, as presented in Fig. 11, for a given ratio between the condensation temperature $T_L$ and the critical temperature $T_C$, the thermal efficiency of RC ($\eta_{RC}$) is strongly dependent on the evaporation temperature $T_H$ [1]. It suggests increasing the evaporation temperature would be the most beneficial means for the increase of $\eta_{RC}$. This implies a higher efficiency tend to be obtained by using high-boiling point working fluids. Ringler et al. [36] observed a further change there exists a optimum line of ideal evaporation temperature which corresponds to the maximum efficiency, as shown in Fig. 12 for different exhaust gas temperatures.

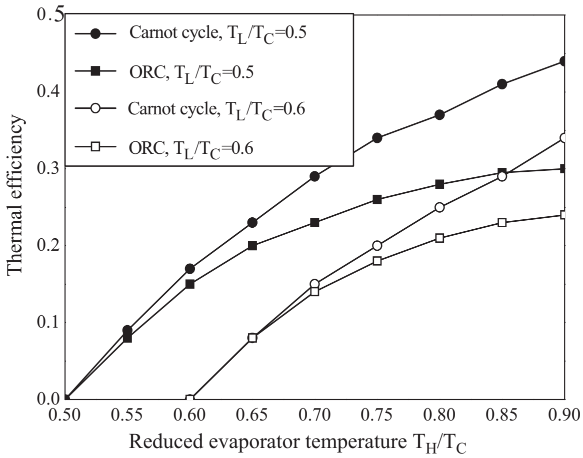


**Fig. 11.** Dependence of $\eta_{RC}$ on the evaporator temperature.

A further increase in the evaporation temperature would decrease the system efficiency.

A similar conclusion was also reflected in works carried out by Mago et al. [57] and Liu et al. [58]. They suggested the critical temperature $T_C$ of working fluid has little impact on $\eta_{RC}$, although $\eta_{RC}$ for working fluids with lower critical temperature is lower. Previous study conducted by Lee et al. [59] also showed that $\eta_{RC}$ for the most potential working fluids are within ±10% range of CFC-113. However, the maximum value of the total heat recovery efficiency is different. Liu et al. [58] found that it occurred at the appropriate evaporating temperature between the inlet temperature of waste heat and the condensing temperature, and was directly and inversely proportional to the inlet temperature of the waste heat source and the critical temperature of working fluids, respectively.

In addition, results of Teng et al. [1] suggested the expansion work varies mainly with the working fluid enthalpy across the turbine for the turbine Rankine engine, or with the working-fluid internal energy across the expander for the reciprocating Rankine engine. This was expressed further by Ringler et al. [36] that, the higher the evaporation enthalpy of working fluid, the greater the work output of a steam process would be achieved for a given process temperature gradient.

For on-road vehicle applications, Teng et al. [1] indicated the size of all heat exchangers (should be as small as possible) also affect the working fluid selection. This requires the mass of the working fluid to be minimized and the cycle efficiency to be as high as possible. The thermodynamic state of working fluid at the end of expansion influences the condenser size. The boiling point, critical temperature, and latent heat govern the effectiveness and cost of the condenser, the evaporator, etc. Generally speaking, for the stationary systems, which almost operate at a steady condition, the most efficient point is considered as a key parameter to working fluid selection. However, for most systems where the waste energy level is variable with the engine operation conditions, the highest efficiency depends on the temperature range of the system operations [1].

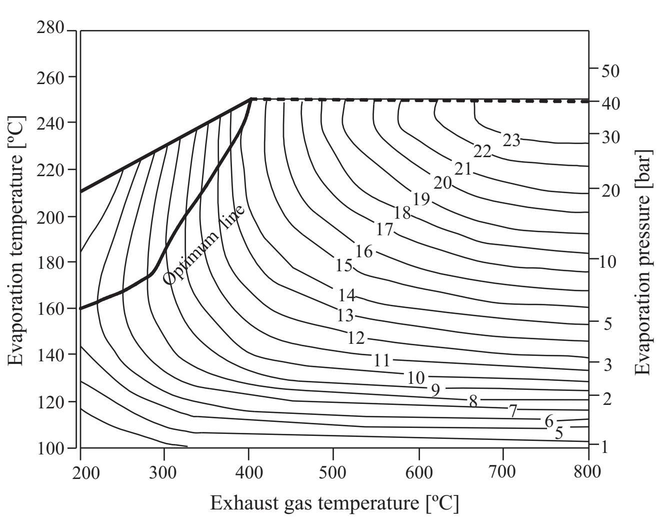


**Fig. 12.** System efficiency of a water Rankine process as a function of evaporation and exhaust gas temperature for EHR system at $T_L$ = 90 °C.

In summary, the selection of the working fluid is critical to achieve high thermal efficiencies as well as optimum utilization of the available heat source. Generally, there is a wide selection of working fluids that could be used in RC applications. Maizza and Maizza [60,61], Vijayaraghavan and Goswami [62] are some of the researchers who have reported performances and characteristics of different working fluids for waste heat recovery systems. The working fluids investigated can be classified into three types – wet, dry and isentropic fluids, in accordance with the slope of the saturated vapor line in the temperature–entropy (*T–s*) diagram.

### 5.1. Wet fluids

Teng et al. [1] characterized wet fluids as having a negative slope for the saturated vapor line, with the expansion generally ending in the two-phase (wet) region. Most of inorganic fluids are wet fluids, such as water, ammonia, etc. Water, as a traditional working fluid for the RC, is the most frequently used working medium for large scale steam RC in power plants [63]. Bayley [64] considered water to be the most practical working medium for thermal recovery cycles due to its appropriate properties, such as most environmentally friendly, safest, better heat transfer characteristics. However it has also some shortcomings, such as freezing, high corrosiveness as a superheated vapor and air infiltration.

Chen and Lin [65] addressed the possibility of a multi-stage RC with the first stage operating on water to recover high temperature exhaust waste heat, followed by a second stage operating on R-11 (Organic solvent) to enable low temperature EHR. They predicted 15% improvement in efficiency through RC–EHR. Ringler et al. [36] concluded that water exhibits the highest evaporation enthalpy (~2250 kJ/kg), delivering the maximum work output and the highest thermal efficiency among the listed working fluids. It is the preferable working fluid for exhaust temperature ranging from 500 to 800 °C. Arias et al. [47] and Endo et al. from Honda [6] also chose water due to the same reasons, as well as its relatively high critical temperature and relatively good transport properties.

Although water could be considered as a candidate working fluid for most heat recovery system based on the Rankine steam process, especially for the EHR, Ringler et al. [36] pointed out its utilization on waste heat recovery might be limited by some technical restrictions. Particularly for the case of IC engine heat recovery applications, Quoilin and Lemort [50] found the selection of the working fluid is strongly correlated to the choice of the heat source(s). A difficulty associated with water is the need for superheating to prevent turbine blade erosion [37,63,66,67]. Teng et al. [1] suggested that a high degree of superheating and reheating, as used in the power-generation steam RC, may not be possible in a vehicle RC–EHR system due to the relatively low temperature at vehicle's part load conditions.

Chammas and Clodic [2] even thought it is far from ideal given its high operating boiling pressures, low condensing pressures and high triple-point temperature. In addition, its freezing point (0 °C) is not as low as desired for an automotive application [36]. Due to these shortcomings, there is concern of a steam RC for small

scale application, in particular for recovering heat of automotive IC engine, it could lead to a complex system requiring large size equipment and high investment. Therefore, Chammas and Clodic [2] argued that other working fluids have to be studied and compared to water in order to define the most suitable candidate for the RC utilizing the exhaust heat of an automotive IC engine.

### 5.2. Dry and isentropic fluids

Most organic fluids are either dry fluids or isentropic fluids, except for some small-molecule fluids such as methane and ethane. Benzene, R113 and R245fa are representatives of dry fluids, which have a positive slope for the saturated vapor line if the state is not very close to critical point (Cp). For this type of fluids, the expansion process ends in the superheated vapor (dry) region. And R11, R12 and R134a are examples of isentropic fluids, which have almost vertical slope of vapor saturation curve in the *T*–*s* diagram in most of the temperature range and thus, in an isentropic expansion process, the working fluid basically remains as the saturated vapor [1,30].

Generally the characteristics of dry and isentropic fluids eliminate the concerns of damage of liquid droplets on the turbine blades caused by wet steam and the use of superheated apparatus [1,58,68]. Zhang et al. [68] suggested this is one of the main reasons why organic working fluid is adopted as the working fluids used in the RC. However, in term of performance, Hung et al. [69] argued this property of dry or isentropic fluids would reduce the area of net work in the *T*–*s* diagram. Additionally, in order to relieve the cooling load of condenser, it is widely acknowledged a recuperator is necessary for cooling the superheated vapor to the saturated state. This gives rise to an addition cost [1,69]. Teng and Regner [48] suggested operating EHR system with a supercritical cycle at the expense of increased pump pressure to eliminate those problems. Verschoor and Brouwer [63] suggested further the exergy losses at the heat transfer can be reduced by decreasing the temperature differences. The study of Teng et al. [37] found that a carefully selected organic fluid can minimize the temperature difference between waste heat and the working fluid. They concluded for HD diesel engines from which waste heat temperatures are of the moderate level, the most efficient and highest power output are usually achieved by using a suitable organic fluid instead of water as the working fluid for the RC. On the other hand, analysis by Somayaji et al. [2,56,70] demonstrated dry and isentropic fluids show better thermal efficiencies, considering their relatively low triple point temperature means the fluid does not solidify after passing through the turbine, as opposed to wet fluids that produce condensates after the turbine.

Chammas et al. [2,30] performed a second law analysis and concluded the second law efficiency would decrease with turbine inlet temperature due to the increased irreversibility, as shown in Fig. 13 [57]. As it was found the cycle thermal efficiency is a weak function of the turbine inlet temperature [2,30,70], it was recommended it is not necessary for organic fluids to be superheated. Consequently, the optimum efficiency of a RC working with a dry fluid could be achieved when the fluid operates along the saturation curve without being superheated [47,57,66,67].

With regard to the superheating, Teng et al. [1] proposed that, while superheating in an organic RC–EHR system would be restrained by the thermal stability temperature $T_{stability}$, as is shown in Fig. 14, the thermal efficiency for a RC could increase with the degree of superheating. Because of the fact that water has the strongest hydrogen bonds, giving it the highest thermally stability [1,63], steam RC would therefore have higher efficiency than those listed fluids in the study by Ringler et al. On the contrary, most organic fluids have relatively low thermal instability temperatures [1], hence as suffer chemical decomposition and deterioration at high temperatures and pressures [2,30].

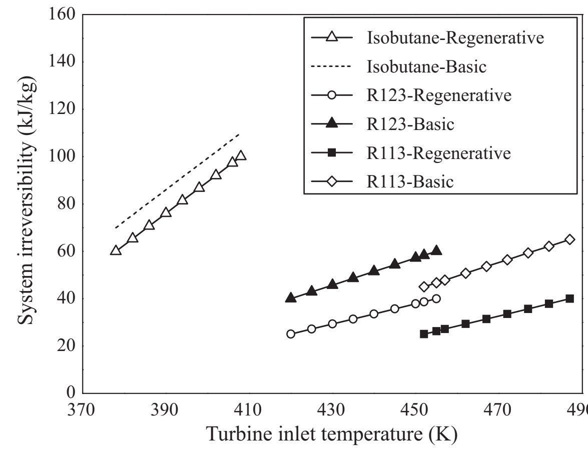


**Fig. 13.** Variation of the system specific irreversibility with the turbine inlet temperature (Pe = 2 MPa).

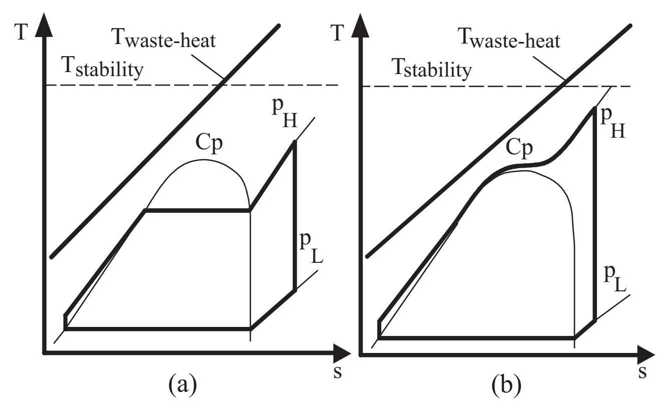


**Fig. 14.** Supercritical RC–EHR: (a) subcritical cycle with superheating; (b) supercritical cycle.

Considering the importance of working fluid characteristics to the system performance, Teng et al. [1] proposed a concept of binary mixture working fluids. The binary mixture was expected to have combined characteristics of both components. The efficiency of organic RC could be codetermined by the two compositions and their thermodynamic properties. They investigated fluorinol-50 (50/50 TFE–water mixture) as an example and found the binary mixture working fluid was beneficial for the thermal efficiency of organic RC due to a higher mean evaporation temperature and a higher mean condensation temperature, which increases the driving force of heat transfer for achieving the same $T_L$.

Research results from Verschoor and Brouwer [63] also demonstrated binary mixture working fluids might benefit EHR efficiency. In their investigation, it was found the evaporation with single medium such as water takes place at a constant temperature, while the finite heat source changes in temperature. This causes an increase in the temperature differences between the heat exchanging fluids. As a result, the exergy losses at the heat transfer process in the evaporator increase. However, these exergy losses can be reduced if the evaporation take place at a variable (gliding) temperature, which is possible with a binary mixture. Investigations on mixture working fluids are still very limited and more work is necessary to obtain a better understanding of their influence on system performance.

## 6. Conclusions

Various technologies including turbocharger/turbo-compounding system, thermoelectric system and thermal RC system are being widely investigated for EHR to increase the total efficiency of IC engine powertrains. For providing an insight into relevant technical details, relevant researches and developments on thermal RC have been reviewed with emphasis on characteristics of possible temperature and heat from exhaust gases, various system configurations, innovations on expanders and working fluids. The following major conclusions are drawn.

Developments on EHR from hot exhaust gas have achieved rapid progress in the past decade. Thermal systems based on RC are regarded as a low cost solution with high total system efficiency, compared to other systems.

Design and selection of thermal operating parameters and systemic configuration for RC–EHR not only depend on combustion engine size and maximum power, but also the application type (stationary powertrain, on-road vehicle or off-road vehicle) which also affects exhaust gas temperature and useful energy (*Exergy*) significantly.

Various system designs, expanders and working fluids (medium) have been investigated and optimized. When the system structure is decided, performances of expander and working fluid for RC system are critical for achieving highest possible system efficiency.

The low system efficiency for thermal EHR is one of the remaining problems, in particular for those applications of on-road vehicles, which normally cannot supply enough high exhaust temperature and can not accommodate too large hardware of EHR system. Attempts should be made to accelerate relevant researches to apply EHR on production vehicles.

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